National Aeronautics and Space Administration

Turbine Hot Section Material Development

Dr. Michael V. Nathal
Chief, Advanced Metallics Branch
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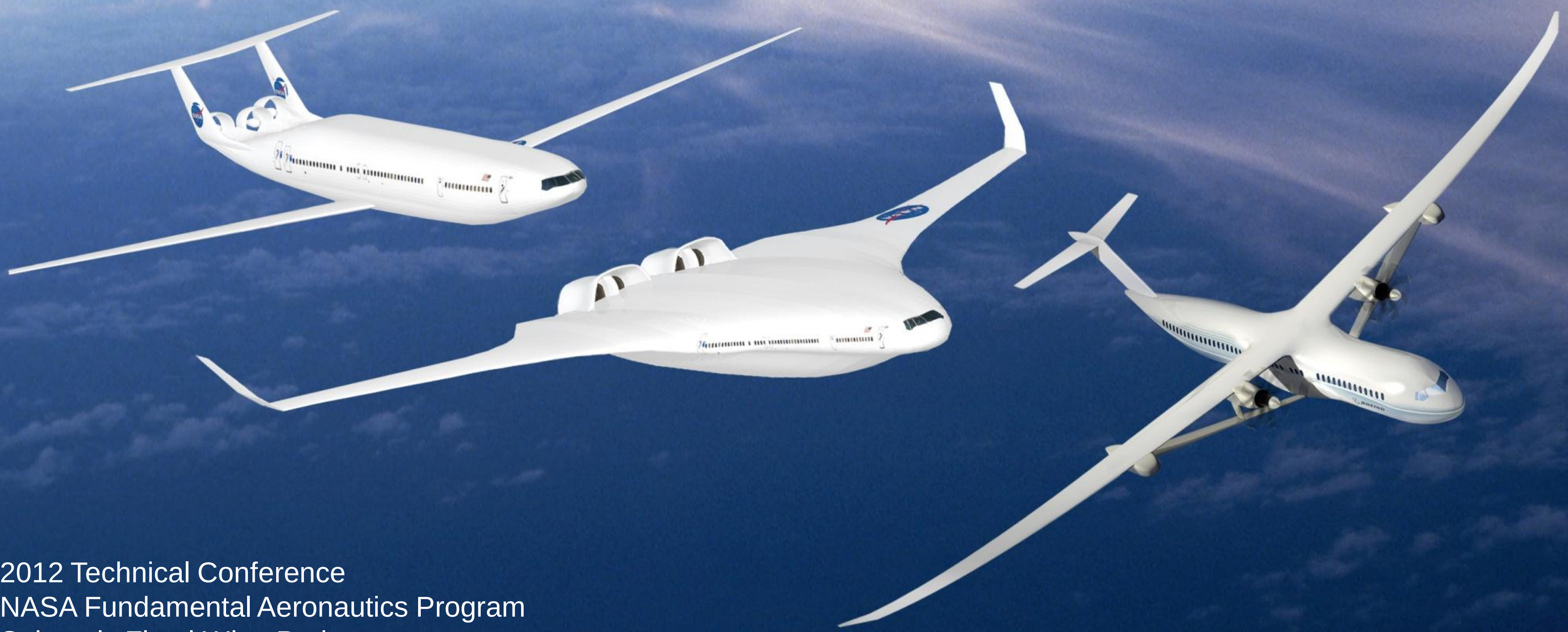


2012 Technical Conference
NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Cleveland, OH, March 13-15, 2012

Turbine Hot Section Material Development

Blade team: Rebecca MacKay, Jim Nesbitt, Tim Gabb, Anita Garg, Rick Rogers, Jim Smialek, Mike Nathal

Disk Team: Tim Gabb, Jack Telesman, Chantal Sudbrack, Susan Draper, Anita Garg, Jim Nesbitt, Rick Rogers, Frank Ritzert

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

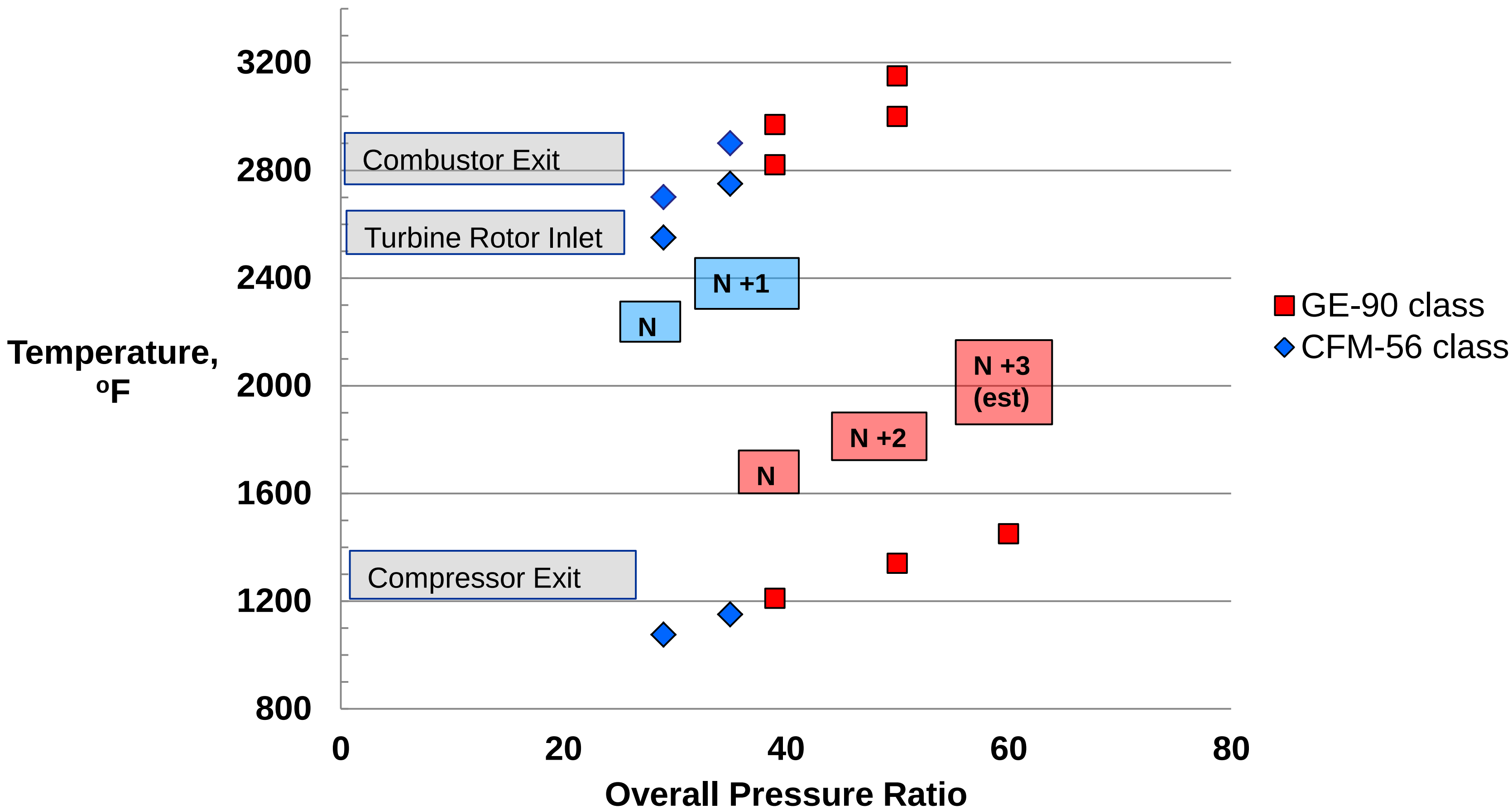
* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

Achieving N+2, N+3 Goals Requires Improved Materials Capability for Increased Turbine Temperatures

System Studies Results



Tong et al, 2009
Guynn et al, 2009
Benzakein, 2008

Roadmap For Metallic Blade System

ver. Oct 2010

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

Low density single crystal alloy optimization

Adv Blade System

Alloy/Bond Coat/TBC/ co-optimization

Component development – ERA follow-on

Creep/fatigue/environment failure mechanisms

Space Act Honeywell

Manufacturing demo

AFRL: Creep/TMF Life Prediction

AFRL: Future blade programs

Unfunded: New superalloys with alternate strengthening mechanisms for +200 F capability

Adv TBC development

Hybrid blades concept screening

Hybrid blades concept development

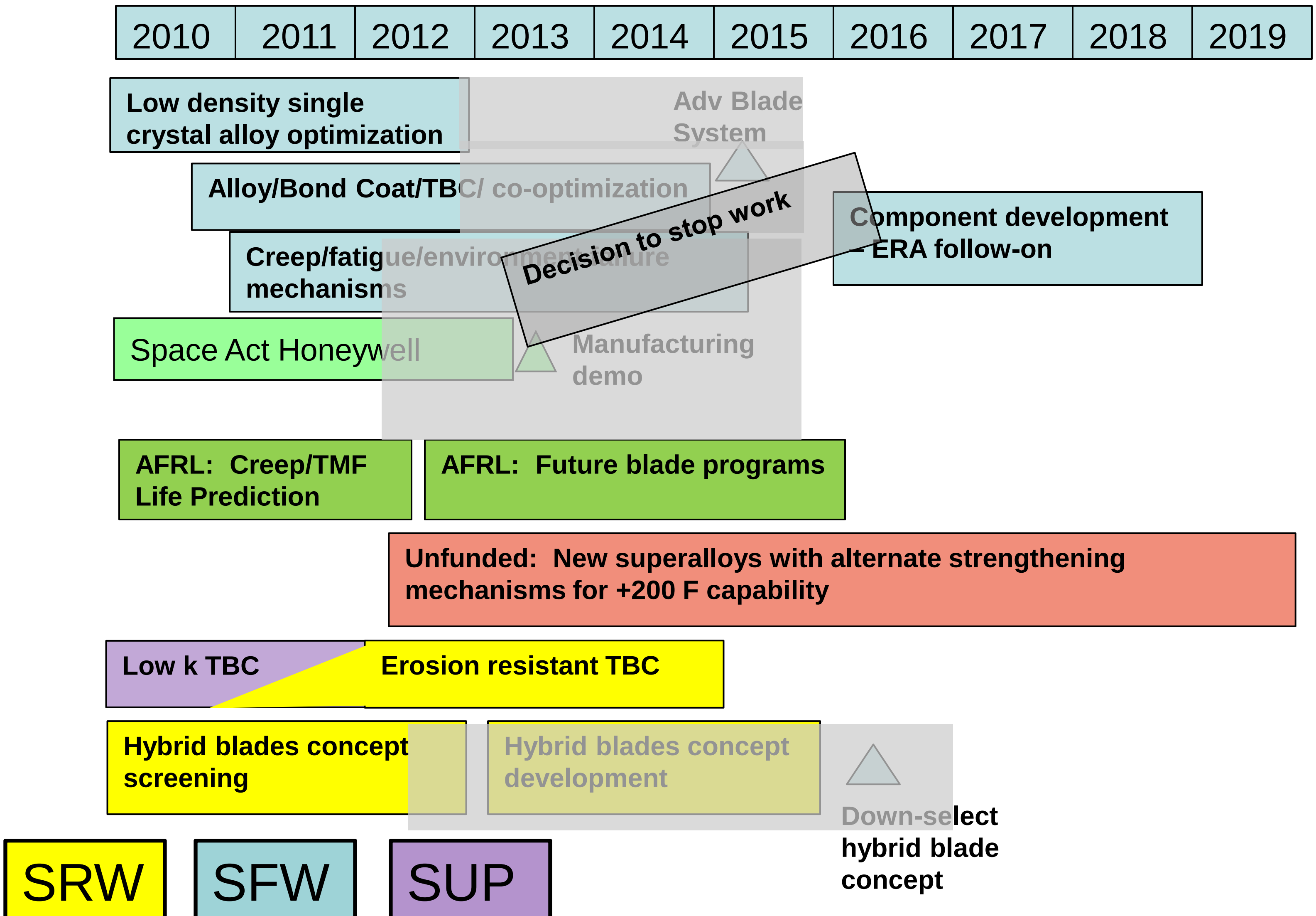
Down-select hybrid blade concept

SRW

SFW

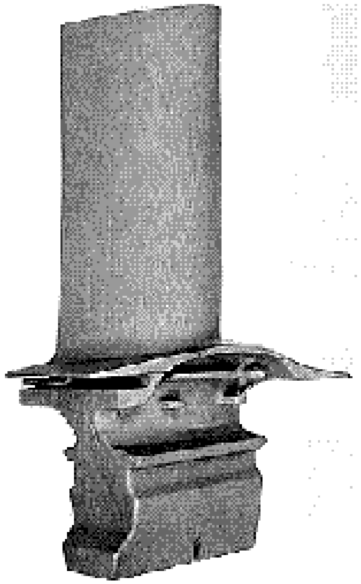
SUP

Roadmap For Metallic Blade System



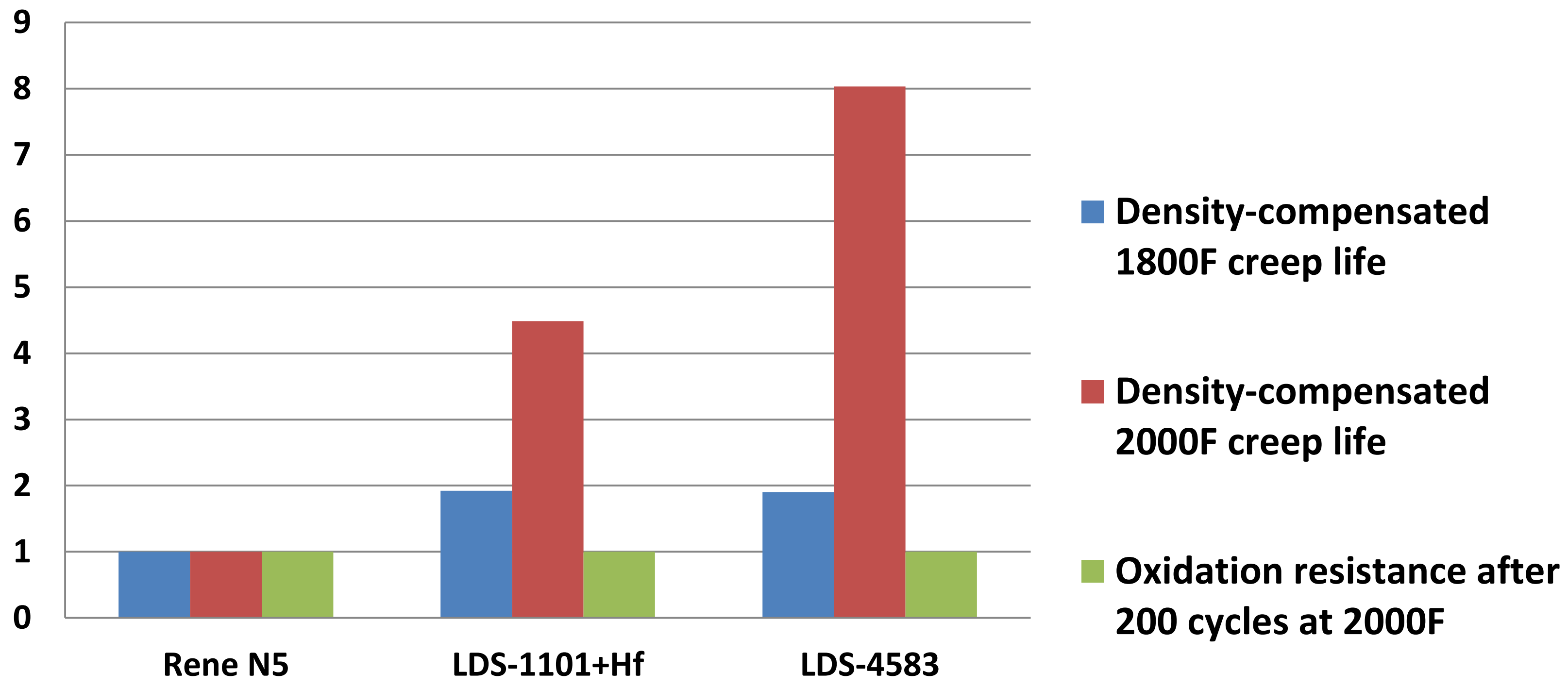
Development of High Temperature, Low Density Turbine Blade Alloys

- **Objective:**
  - Combine experiments and models to develop advanced turbine blade superalloys for a balance of all required mechanical and environmental properties
  - Optimize low density superalloy (LDS) single crystals for transitioning to industry



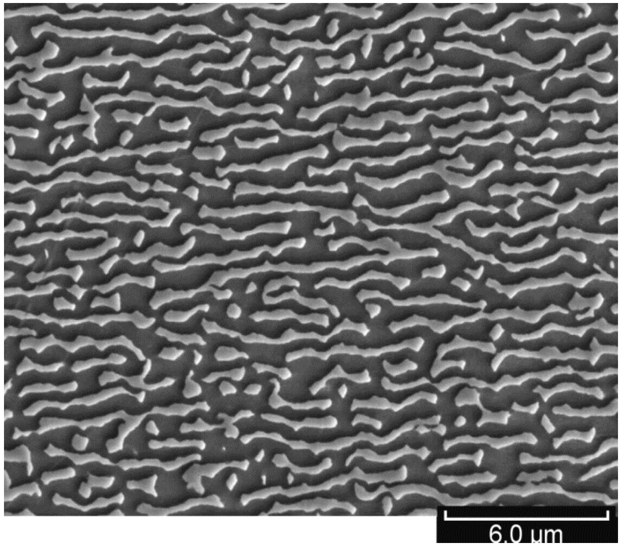
- **Approach:**
  - Design-of-Experiments approach for alloy development balancing creep strength, oxidation resistance, density, and microstructural stability.
  - Compare to predictions from commercially-available software tools based on multi-component thermodynamic modeling
  - Initial LDS alloys identified with +75^{o}F capability; optimization round added +25^{o}F
  - Alloy/Bond Coat/TBC co-optimization
    - Quantify the effect of substrate composition on TBC life with two different bond coats.
    - Quantify the effect of substrate composition and bondcoat on cyclic oxidation behavior without the TBC topcoat

Relative Performance of Low Density Superalloys (LDS) Against Baseline Rene N5

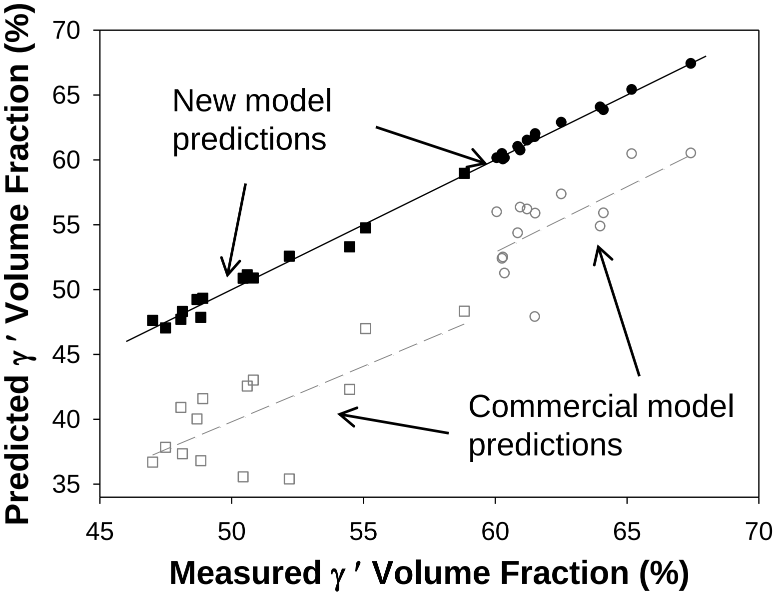


- **Improvements in creep life of patented Round 1 alloy (LDS-1101) over commercial blade alloy (Rene N5) without reducing oxidation resistance**
- **Optimized alloy (LDS-4583) shows further increases in density-compensated creep capability over Round 1 alloy**

Alloy Design Using ICME* Tools: LDS Alloy Data Can Be Used To Improve State-of-the-art Models.



Electron micrograph of alloy microstructure. Volume fraction of dark γ' phase is crucial for alloy strength.

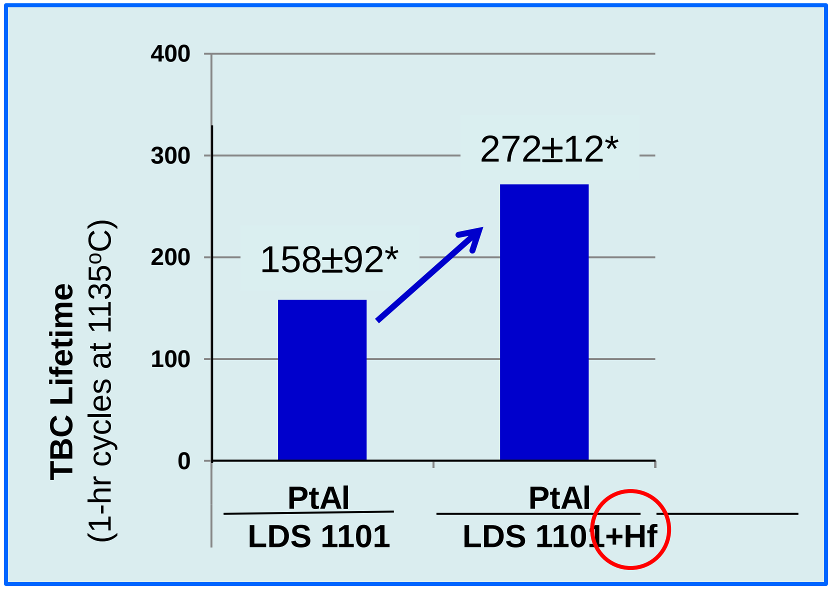


- New models closely predict microstructures from alloy compositions, whereas available, physics-based models grossly under-predicted amount of strengthening γ' phase
- Fundamental studies on influence of microstructural parameters on creep life being finalized and journal article underway

*ICME: Integrated Computational Materials Engineering

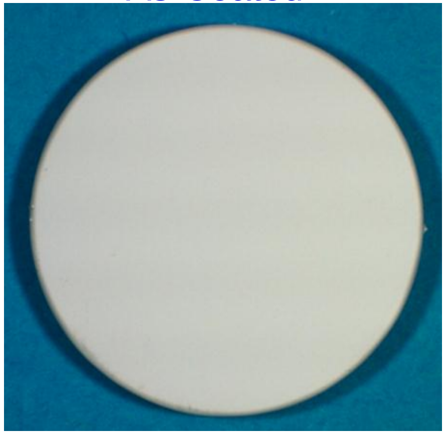
Effect of substrate alloy composition on the thermal barrier coating (TBC) lifetime

Coatings:
- **SOA commercial platinum aluminide bond coat**
- **SOA commercial ZrO_2-7wt.%Y_2O_3 top coat**

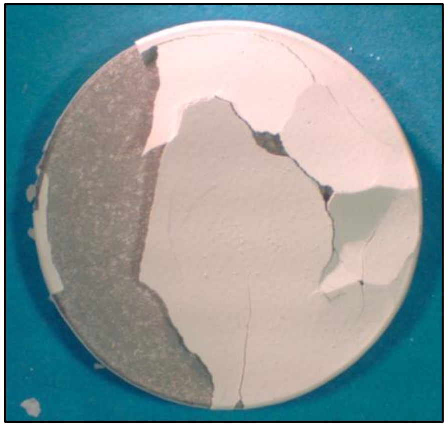


* Triplicate tests

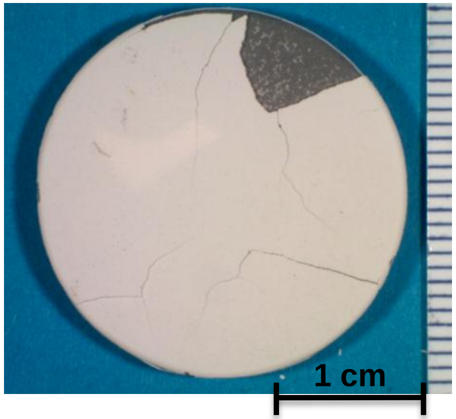
As-Coated



No Hf
105 1-hr Cycles



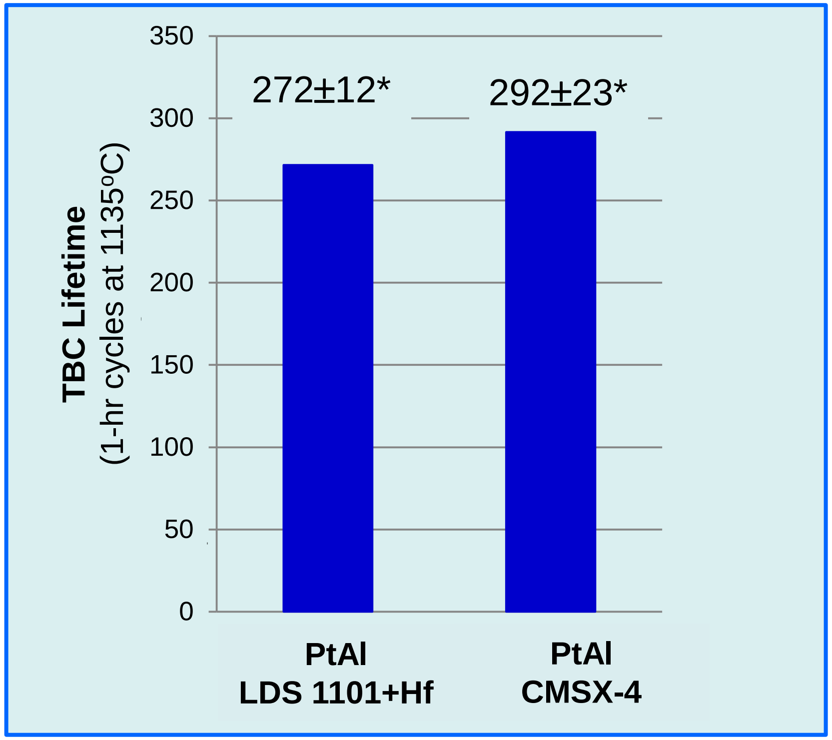
0.15 wt.%
265 1-hr Cycles



Hf addition provides greater TBC lifetime

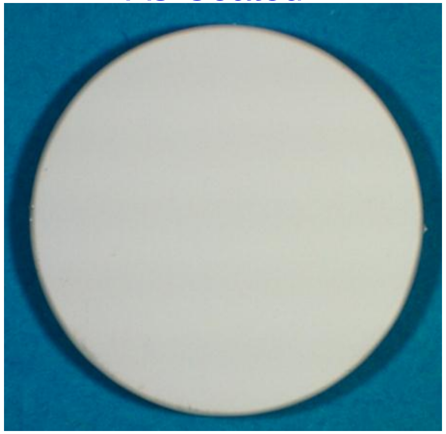
Similar TBC lifetimes observed on LDS alloy and commercial alloy

Coatings:
- **SOA commercial platinum aluminide bond coat**
- **SOA commercial ZrO_2-7wt.%Y_2O_3 top coat**

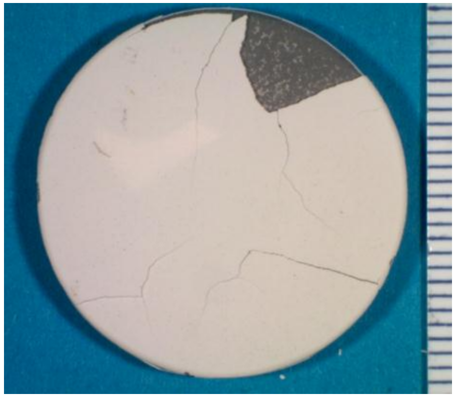


* Triplicate tests

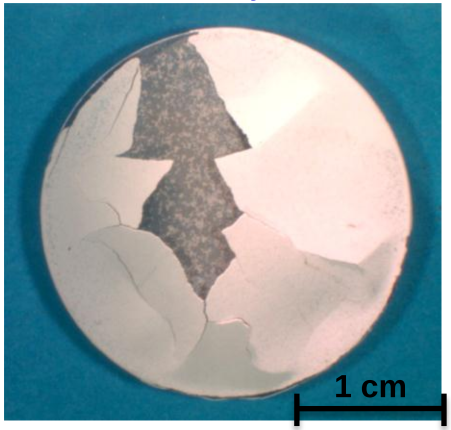
As-Coated



LDS1101+Hf
265 1-hr Cycles



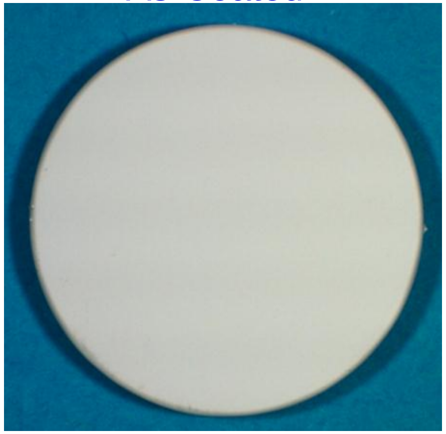
CMSX-4
305 1-hr Cycles

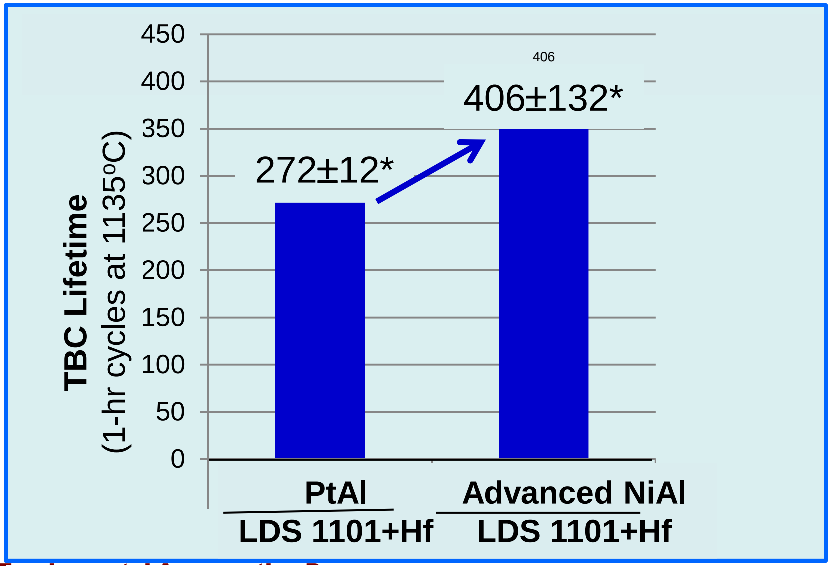


Advanced bond coats show potential for increased TBC lifetime

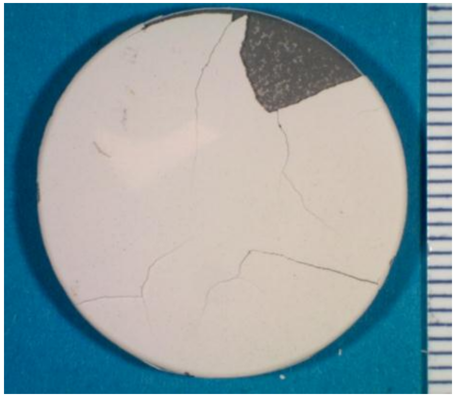
Coatings: (1) SOA commercial platinum aluminide bond coat
(2) Advanced NiAl bond coat
SOA commercial ZrO_2-7wt.%Y_2O_3 top coat

As-Coated

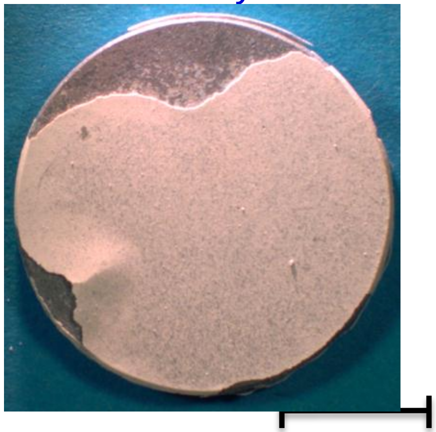




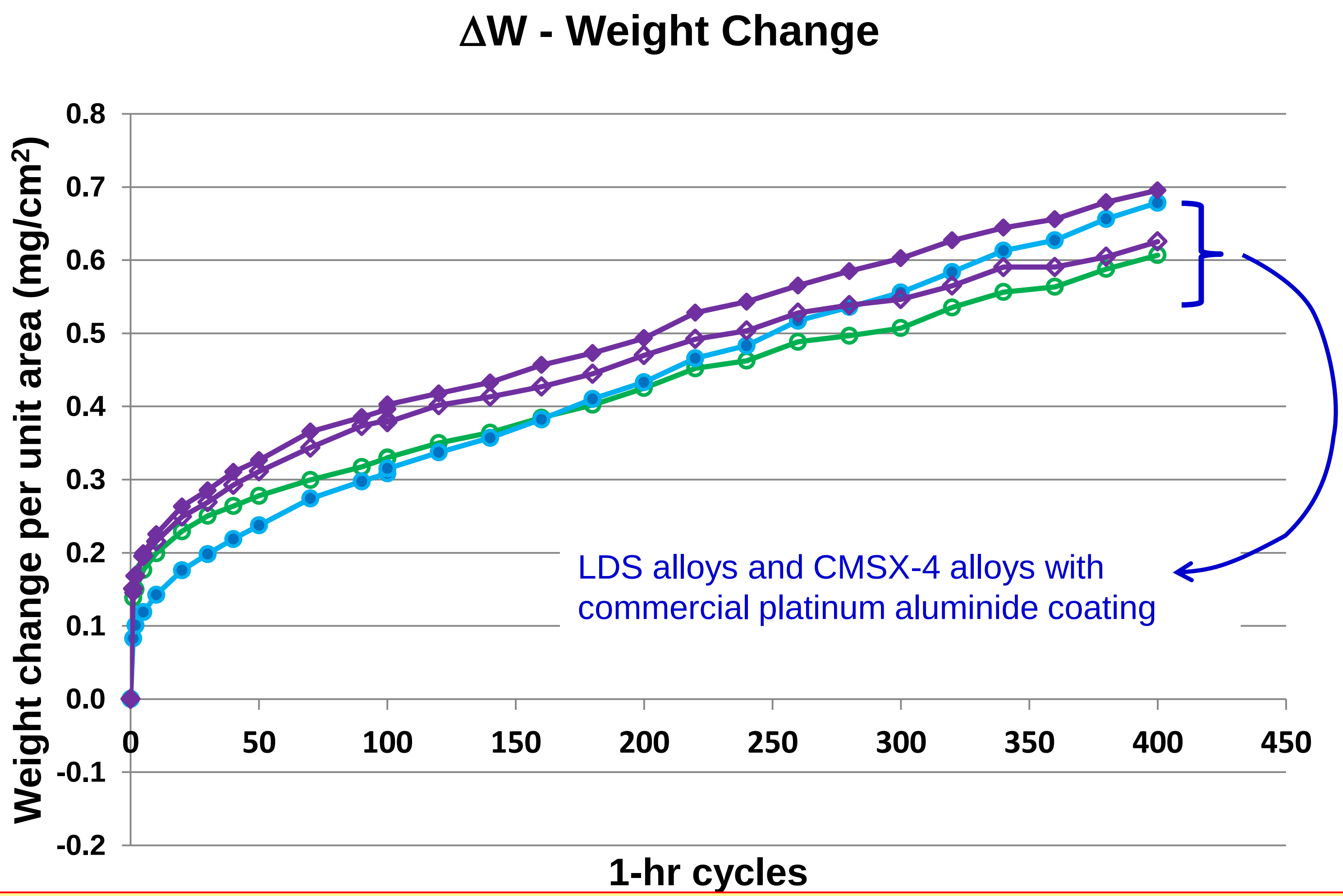
PtAl Bond Coat
265 1-hr Cycles



(2)
NiAl Bond Coat
386 1-hr Cycles

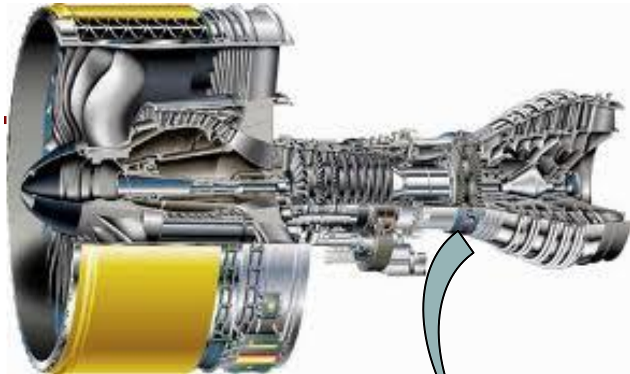


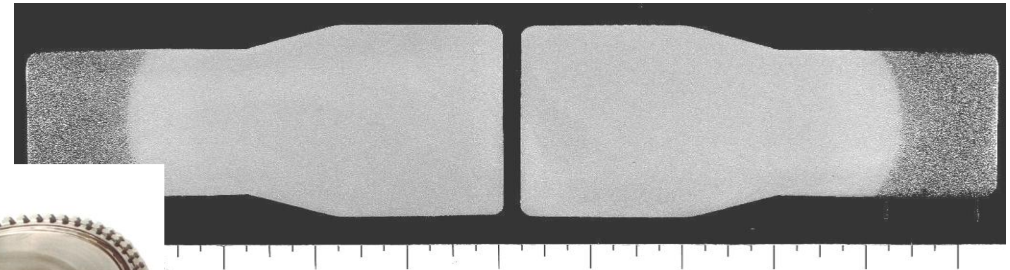
Cyclic oxidation behavior of coated LDS alloys



No difference between LDS and CMSX-4 alloys with commercial platinum aluminide coating,

N+3 ---- 1500°F Turbine Disk





Approach:

- The most advanced turbine disks now in production operate at peak rim temperatures of ~1300°F(704°C) and are made from powder metallurgy (PM) alloys. Dual microstructure heat treatments are used to attain fine grain size in the bore for strength & fatigue resistance; and coarse grain size in the rim for creep & dwell fatigue resistance.
- The Air Force is pursuing an improved PM superalloy, to attain a peak rim temperature near 1400°F(760°C) using this approach.
- NASA SFW needs1500°F(815°C) peak rim temperature to attain N+3 goals. This points to the need for more revolutionary concepts ⇒ **hybrid disk**
- First step: quantify maximum temperature capability of 3rd generation PM disk alloy and cast blade alloys, to select bore and rim materials.

Roadmap For Turbine/Compressor Disks

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

Understand life limiting failure mechanisms for *current* disk alloys and mitigation

→ 1300F disk life system (alloy + coating); in collaboration with industry and AFRL

Feasibility of 1400 F coating

TRL - 6

Understand chemistry-processing-microstructure-relationships *(adv alloys)* to identify development path to 1500F

→ 1400F+ disk alloy system (alloy + coating) concept; collaboration with AFRL and industry.

→ 1400 F disk component development – potential ERA follow-on

Hot spin test

TRL - 5

AFRL 6.2: Hybrid Disk Program Graded Prop Disk processing; Location specific lifing; Next Gen alloy dev.

Downselect 1500F disk concept

TRL - 4

1500 F disk system concept screening (Hybrid disk)

1500 F disk system development

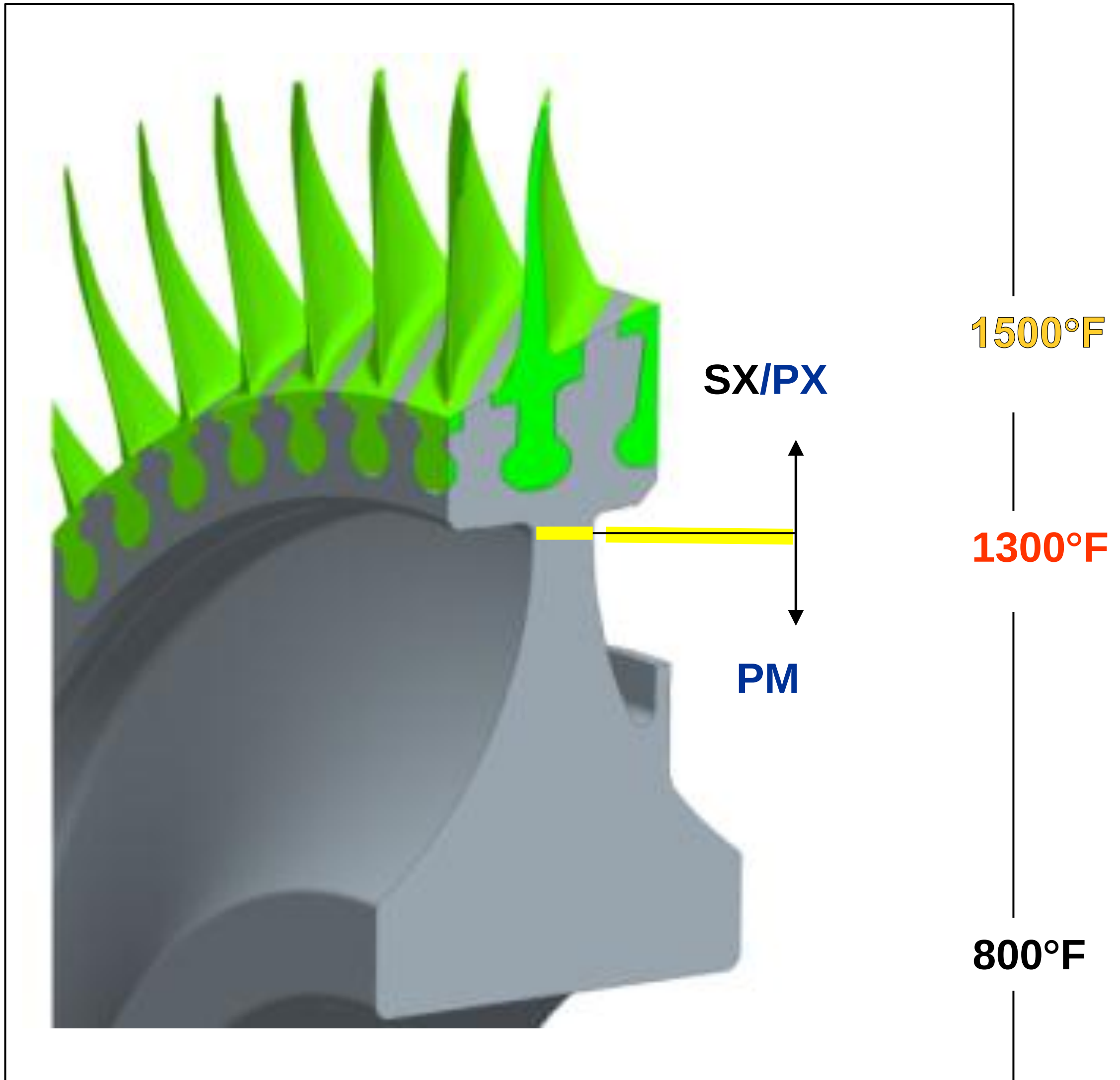
Proposed NRA: Hybrid disk design trade studies

Proposed NRA: Hybrid disk joining dev

Aviation Safety

SFW

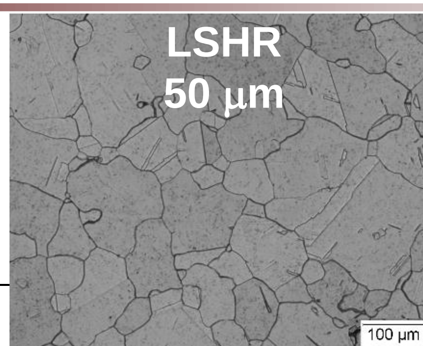
1500°F Hybrid Turbine Disk

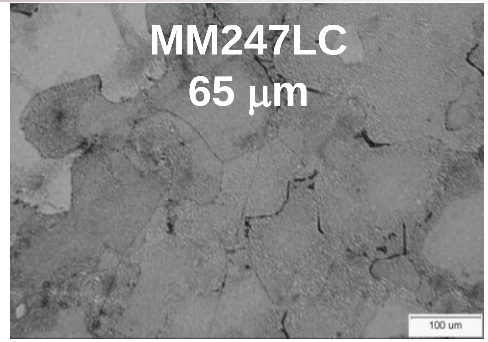


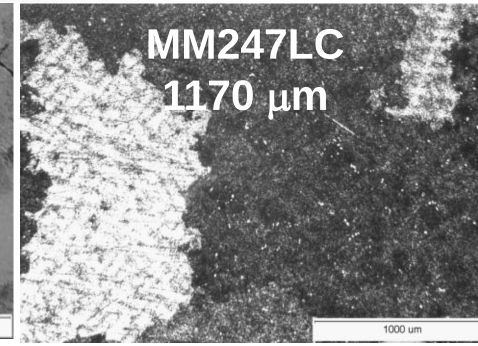
Limited by time dependent properties: creep, creep-fatigue-environment interactions

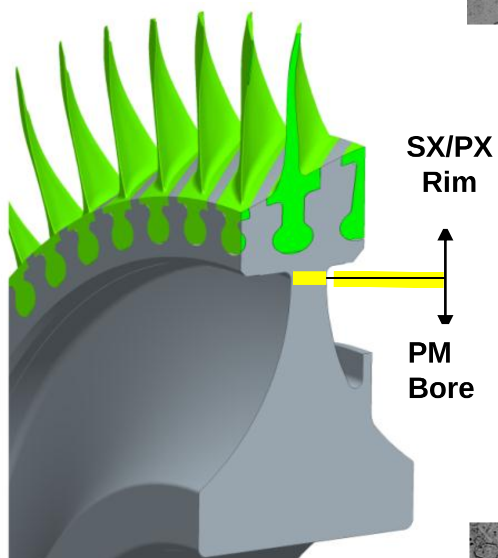
Limited by fatigue and tensile (burst) strength

Varied Grain Size in PM Disk Superalloy LSHR and Cast Blade Superalloy Mar-M247LC, Added Single Crystal LDS

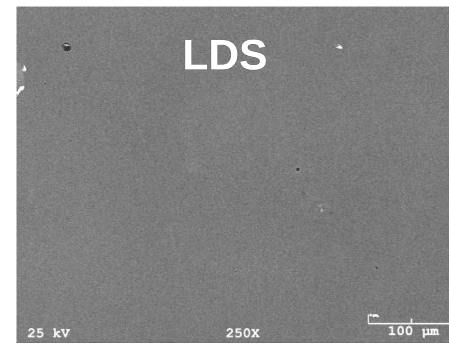




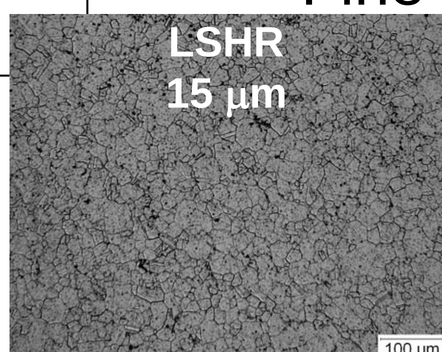


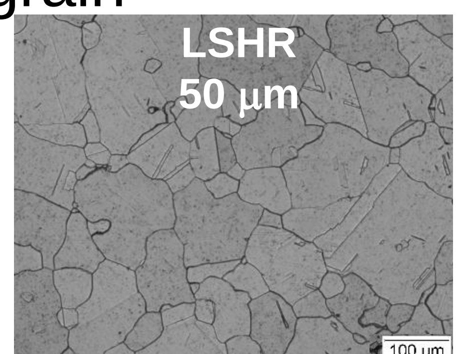


Coarse grain or single crystal

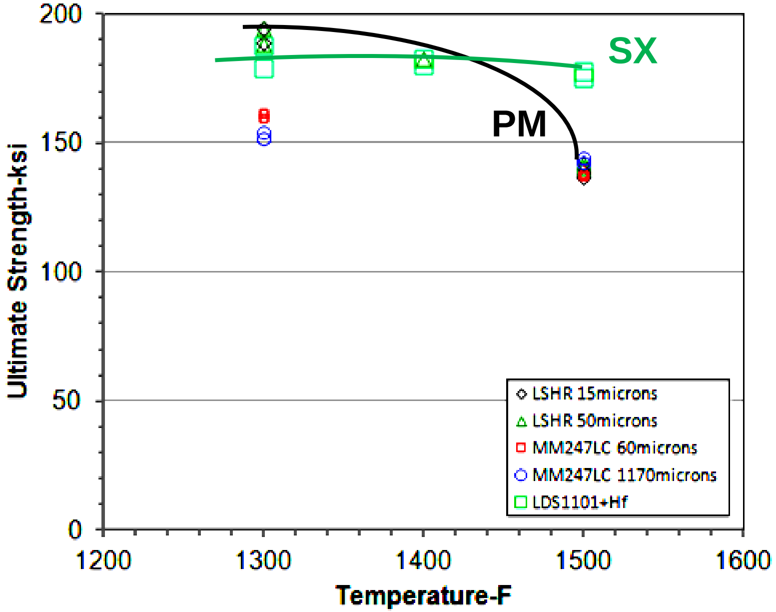


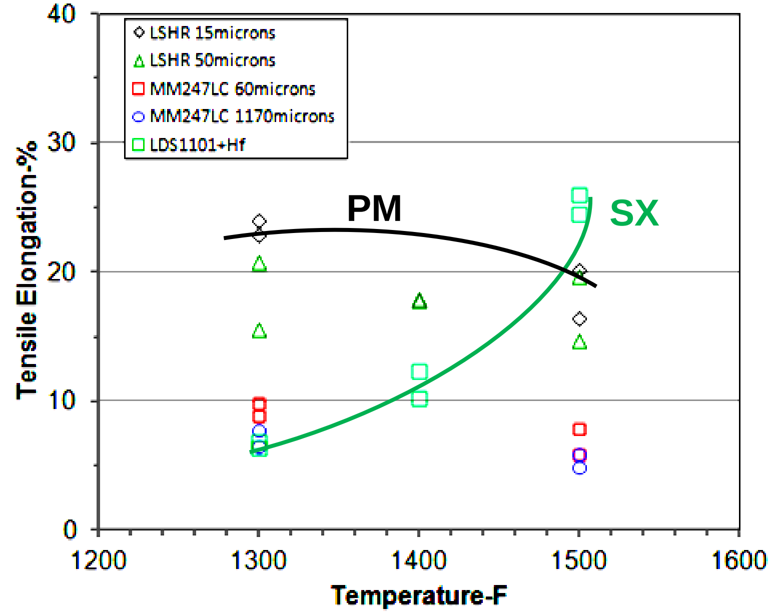
Fine grain





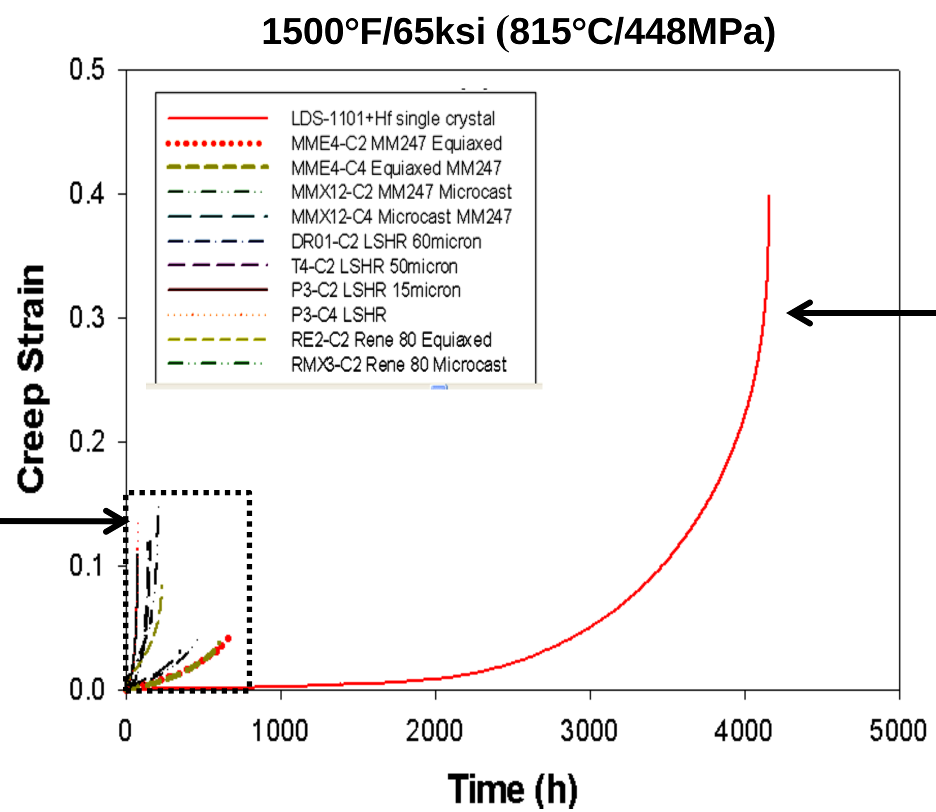
LSHR at 15 μm Grain Size Had Superior Strength and Ductility Near 1300°F(704°C), Needed for Hybrid Disk Bore and Web





But Single Crystal LDS Had Highest Strength and Ductility Near Hybrid Disk Rim Goal Temperature of 1500°F(815°C)

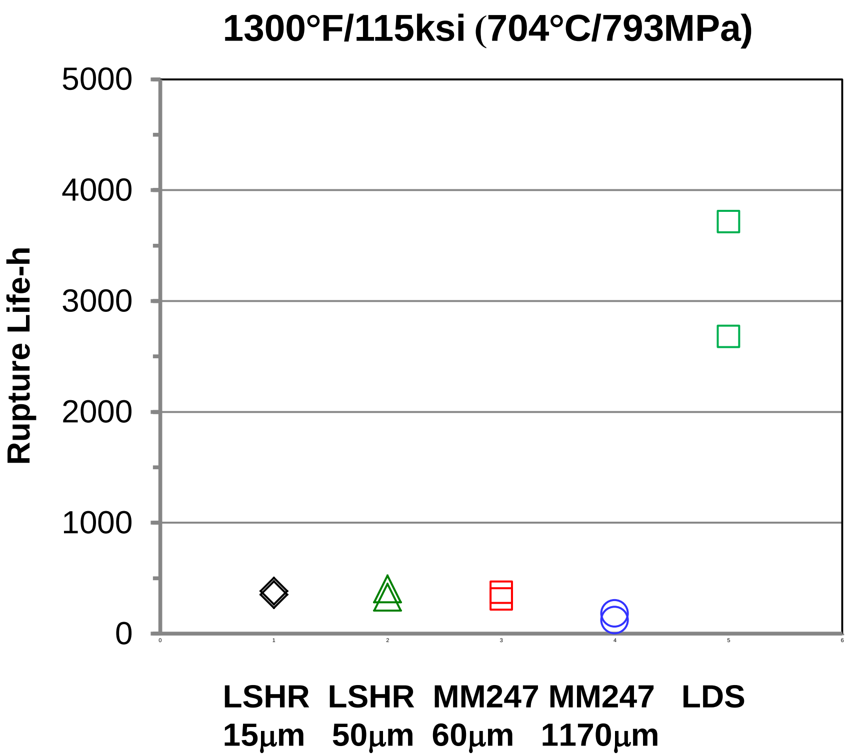
Single Crystal LDS Also Had Superior Creep Resistance at Hybrid Disk Rim Temperature of 1500°F(815°C)

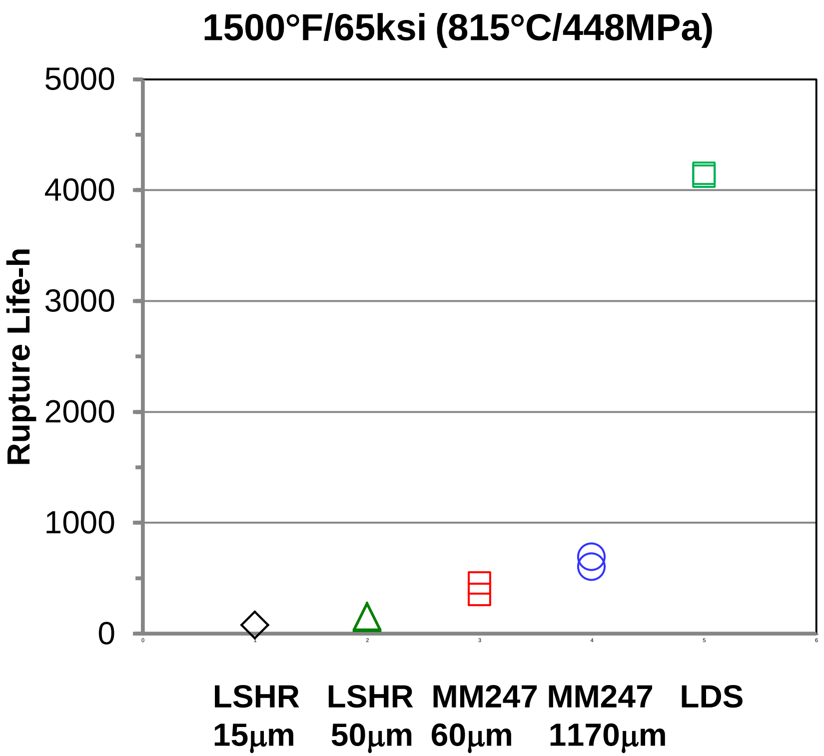


All tested polycrystal-line alloys

Single crystal cast superalloy (LDS 1101+Hf) showed 10X life improvement

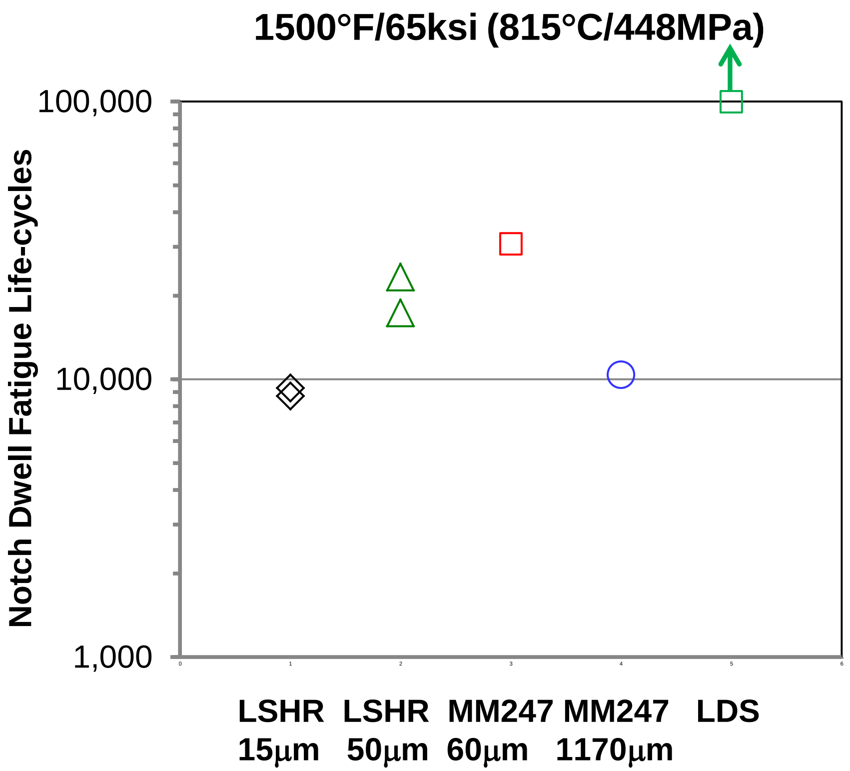
Single Crystal LDS Had Superior Creep Over Hybrid Disk Rim Temperature Range

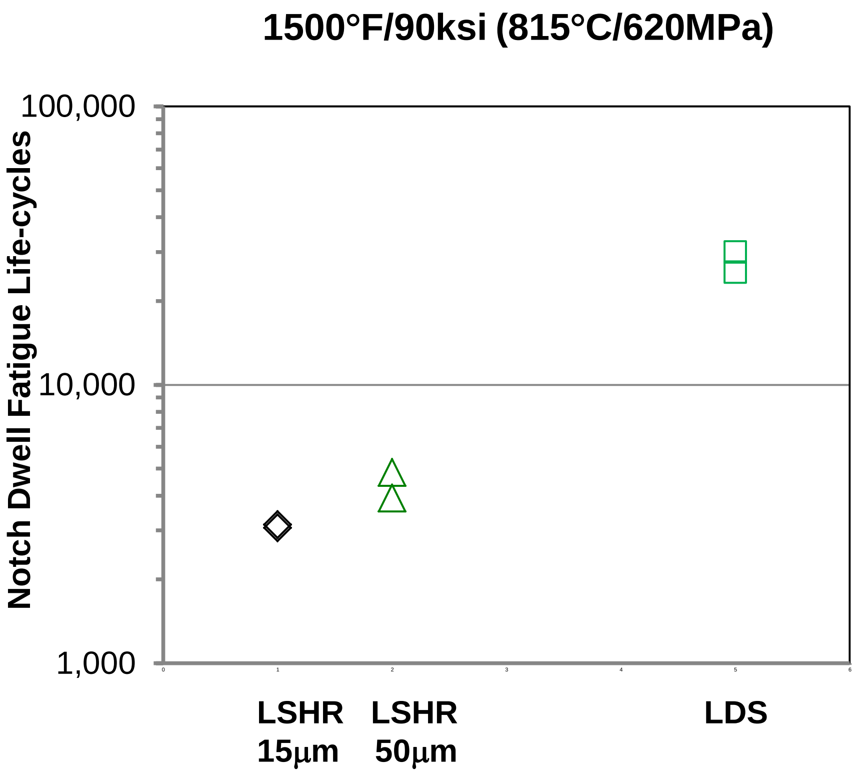




Creep benefit of LDS extends down to 1300°F(704°C)

Single Crystal LDS Showed Better Dwell Fatigue Resistance at Hybrid Disk Rim Temperature of 1500°F(815°C)

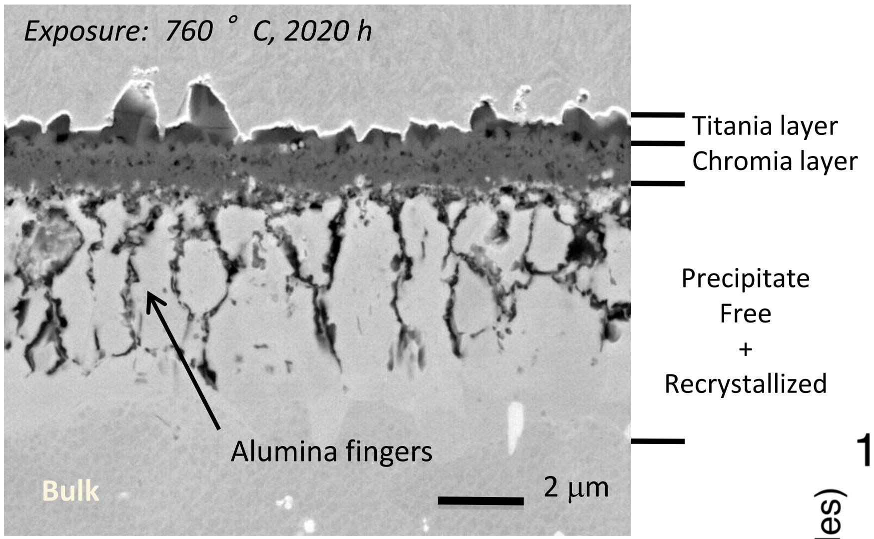




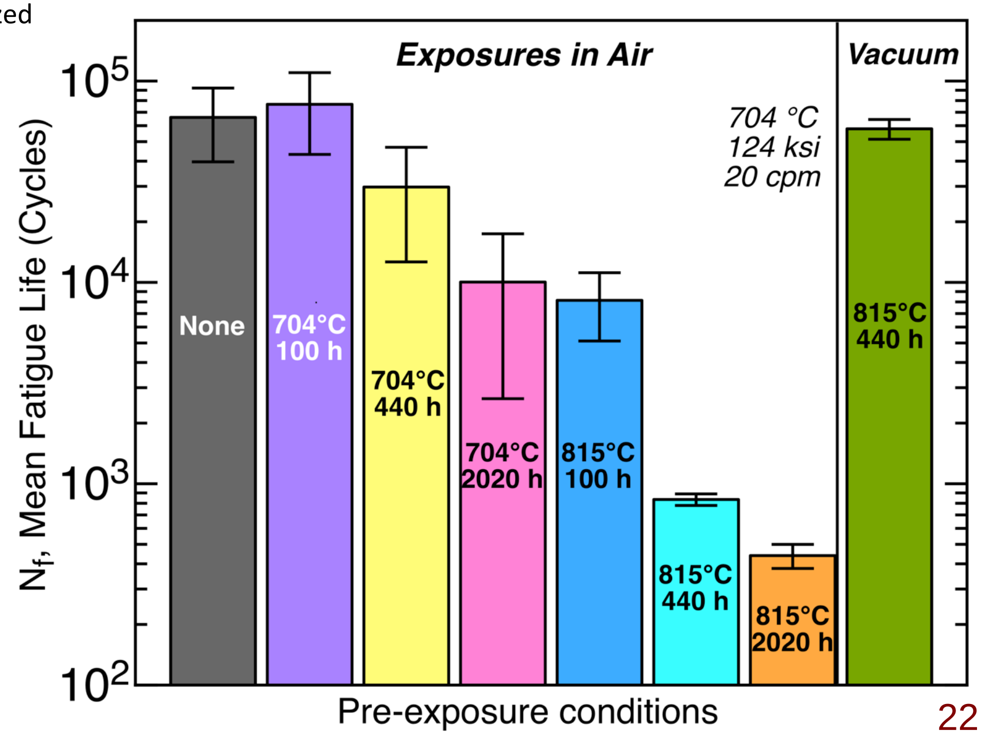
Tests at 1300°F(704°C) now getting underway

Influence of high temperature exposures on notched fatigue life of an advanced disk superalloy

Oxidation damage to ME3 disk surface

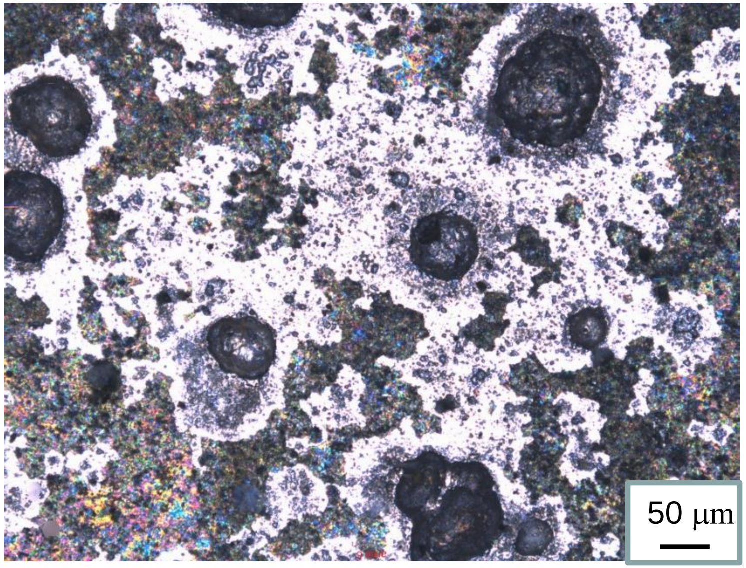


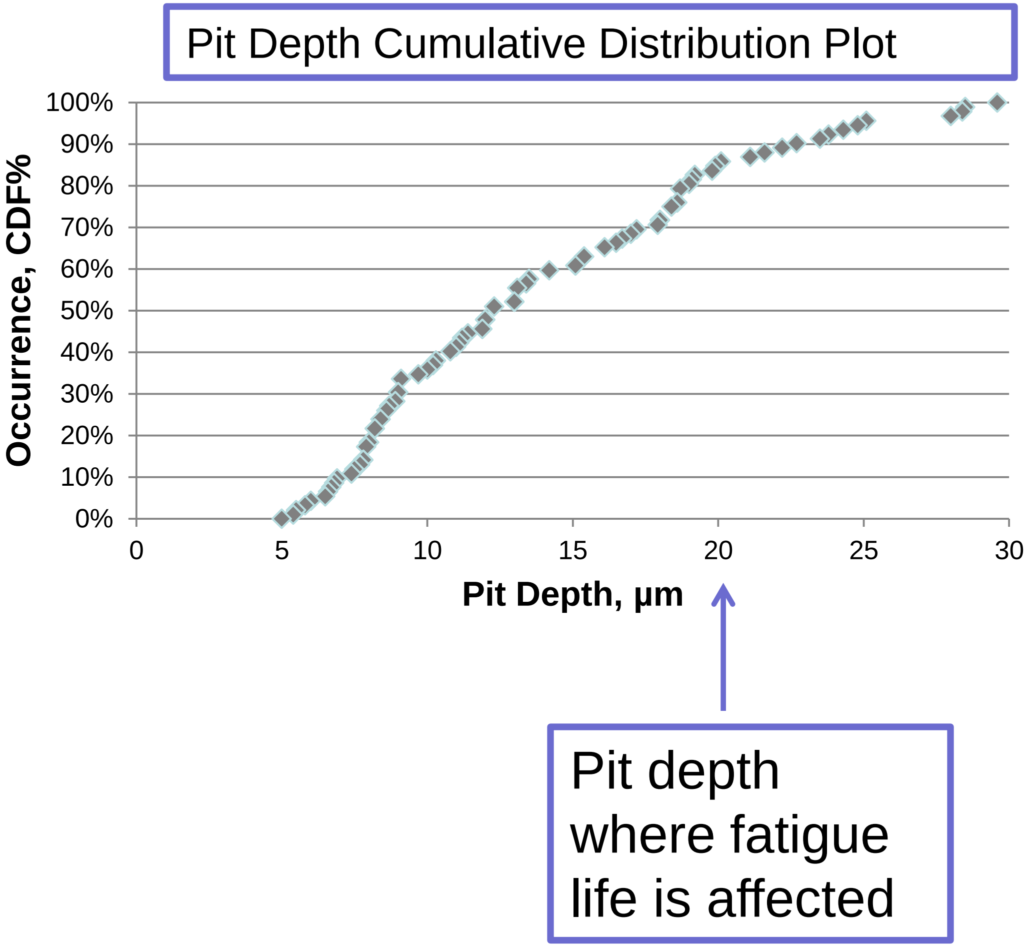
Exposure duration and temperature strongly impact low cycle fatigue response



Hot Corrosion Trials on LSHR

- 32 h corrosion in air at 700ºC using a salt paste of NaS_2O_4 and $MgSO_4$

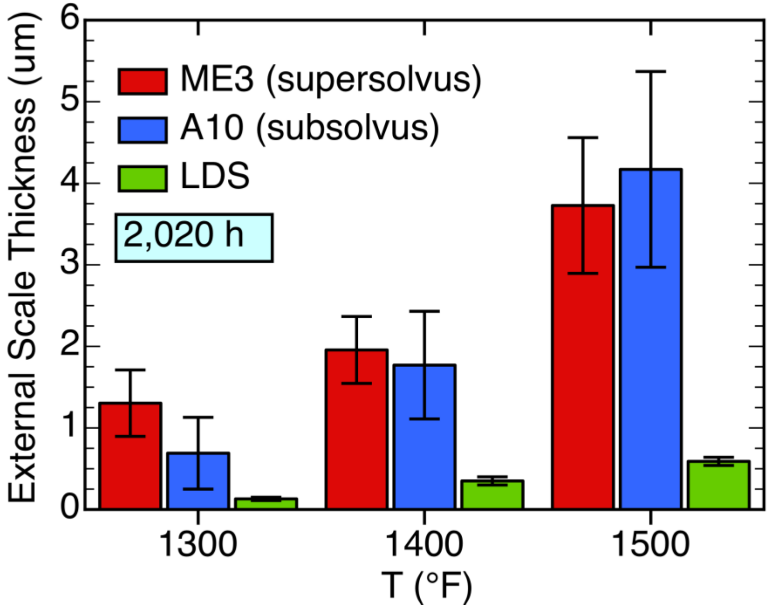




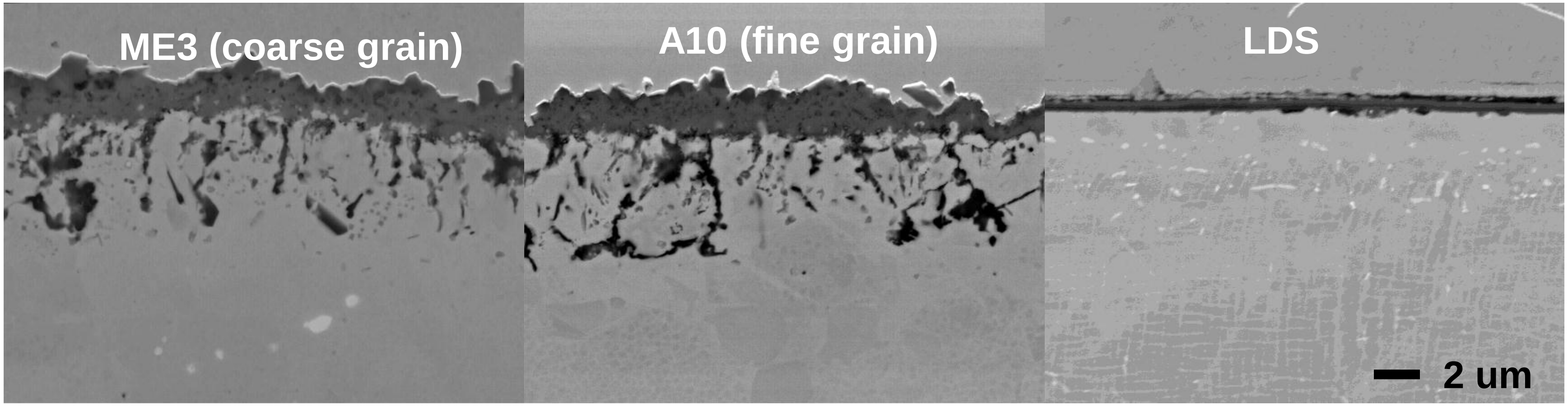
Oxidation Resistance: LDS Showing Slower, More Stable Oxide Growth at Hybrid Disk Rim Temperature of 1500°F(815°C)

Disk alloys ME3, A10, LSHR form Cr_2O_3 external scale with Al_2O_3 subscale

LDS forms Al_2O_3 external scale



815° C (1500° F), 440 h



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AFRL 6.2: Hybrid Disk Program Graded Prop Disk processing; Location specific lifing; Next Gen alloy dev.

TRL - 5

Downselect 1500F disk concept

TRL - 4

1500 F disk system concept screening (Hybrid disk)

1500 F disk system development

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Proposed NRA: Hybrid disk joining dev

Aviation Safety

SFW

Diffusion Brazing Used to Bond Single Crystal to PM Alloy

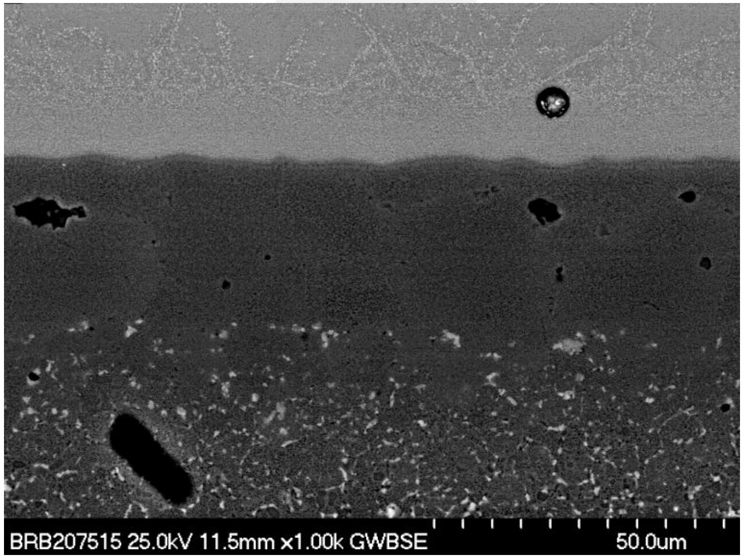
15 min

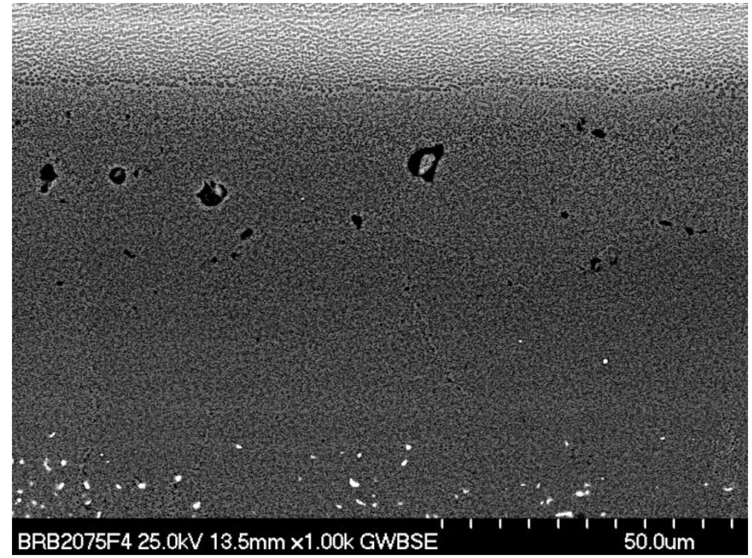
4 hr

CMSX-4

BRB

ME3





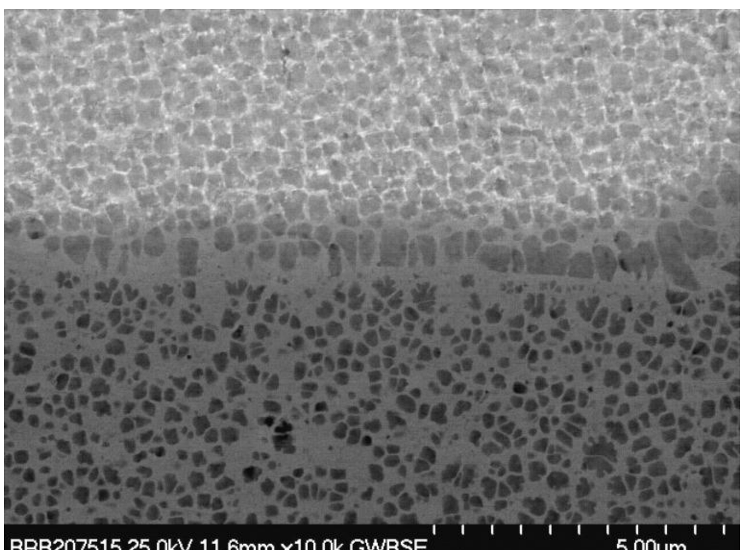
CMSX-4

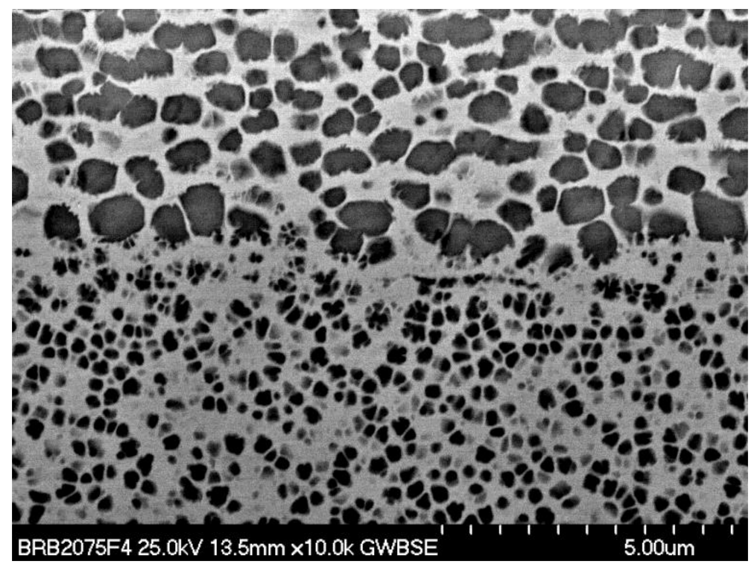
BRB

ME3

CMSX-4

BRB

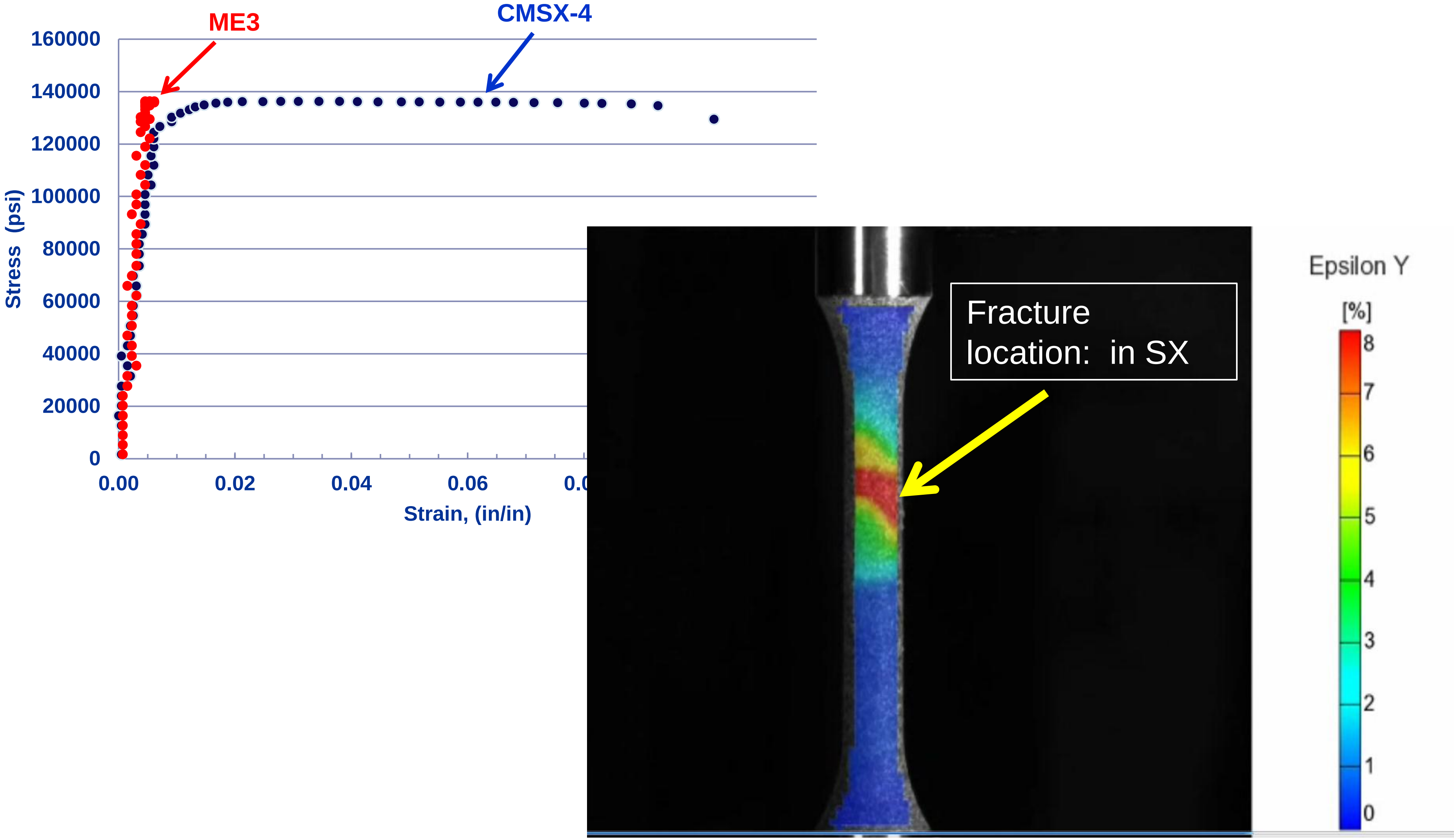




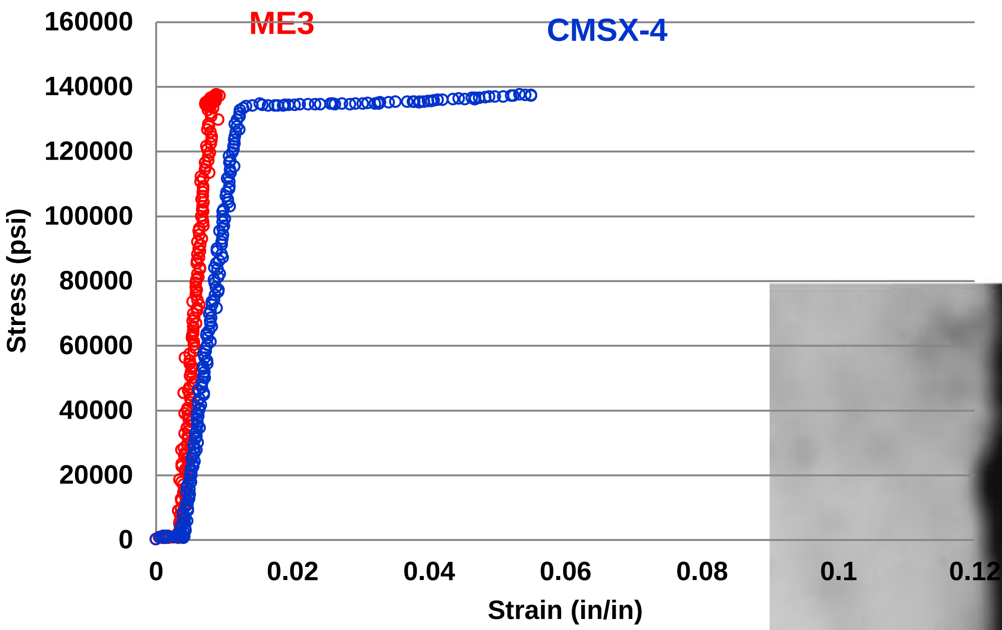
CMSX-4

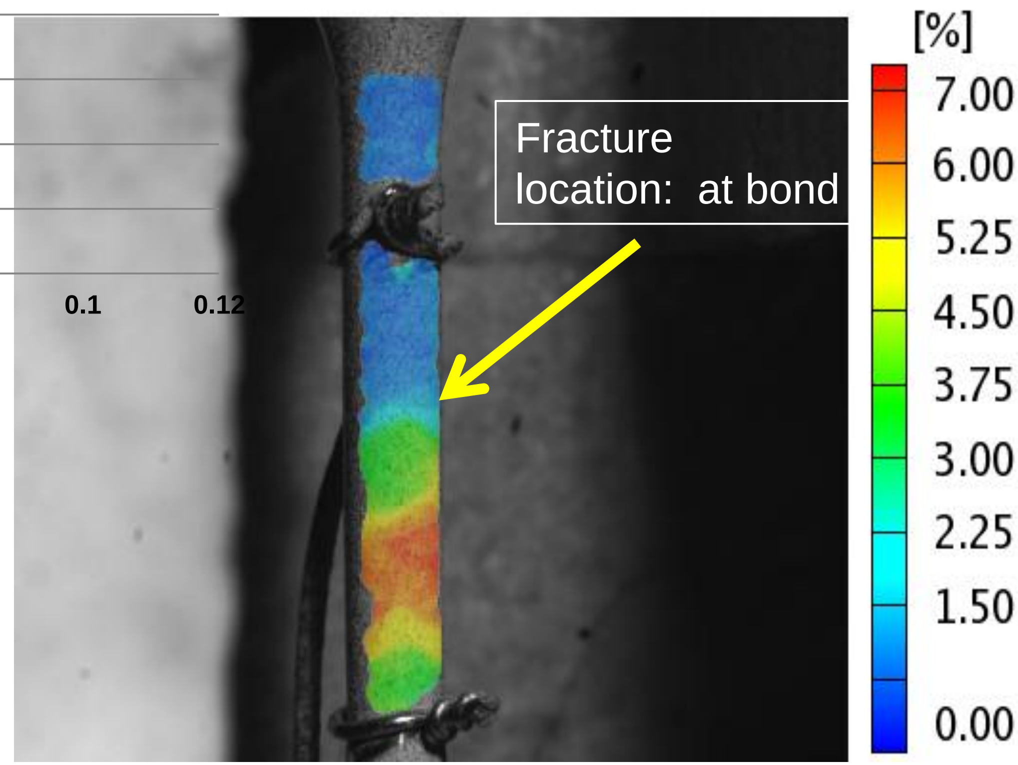
BRB

3D Strain Mapping During Tensile Testing of Hybrid Disk Coupon: ME3/BRB/CMSX-4: Room Temperature

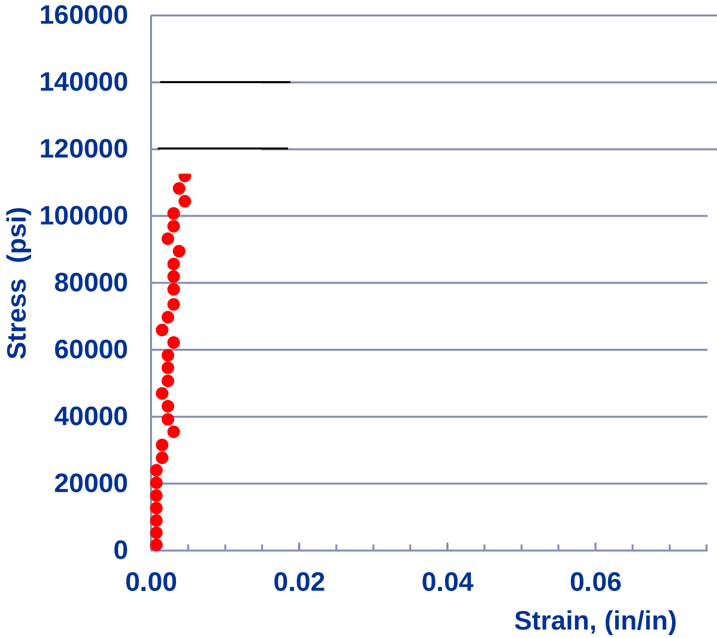


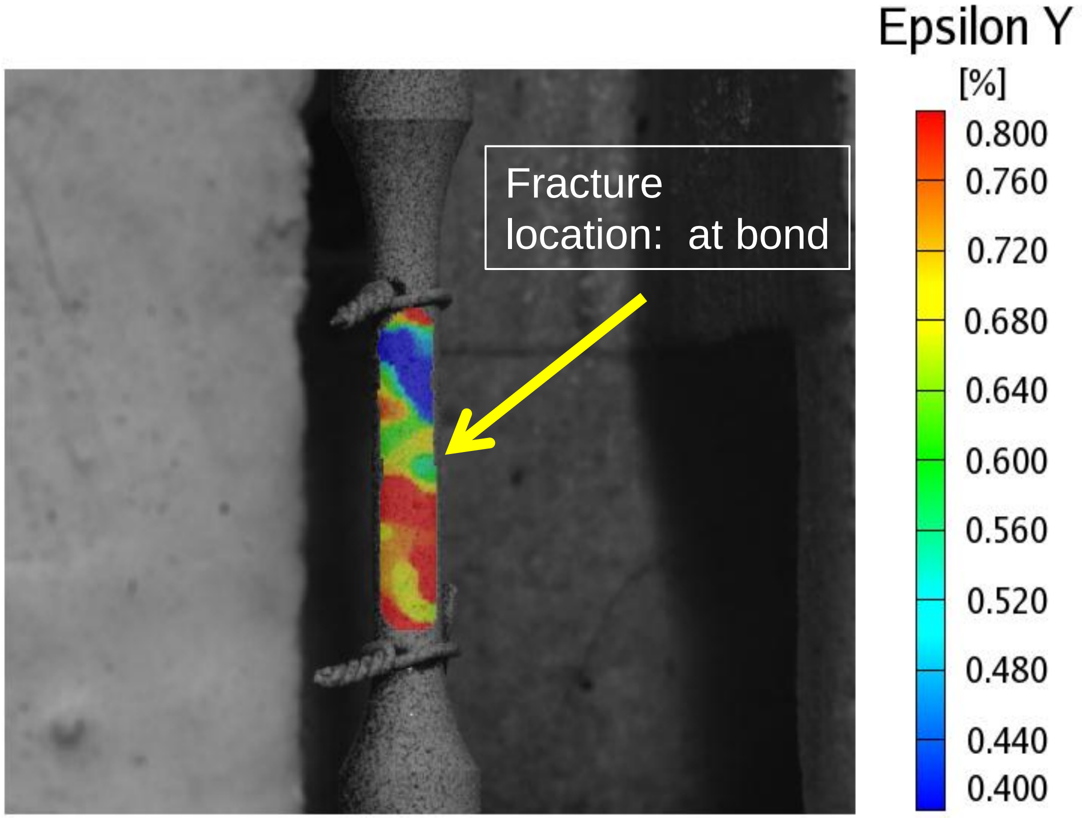
3D Strain Mapping During Tensile Testing of Hybrid Disk Coupon: ME3/BRB/CMSX-4: 650ºF(350ºC)





3D Strain Mapping During Tensile Testing of Hybrid Disk Coupon: ME3/BRB/CMSX-4: 1300ºF(700ºC)





Conclusions

- Low density single crystals have very attractive balance of capabilities for turbine blades :
  - Improved temperature capability at lower weight (+100ºF)
  - Thermal barrier /bond coat compatibility has been demonstrated
  - Looking to expand collaborative efforts with industry
- Compressor/turbine disk development being emphasized via coordinated efforts among NASA, DoD, and industry
  - N+2 requirements point to an extension of powder metallurgy-based approaches
  - Growing importance of environmental effects on mechanical properties
  - Projected N+3 requirements point to a hybrid architecture
  - Some building blocks to hybrid architecture concepts have been addressed
    - Relative performance of PM, SX, and cast alloys in critical mechanical properties
      - Tensile strength, creep life, dwell fatigue life, oxidation and corrosion resistance
    - Mechanical behavior of bonded specimens